The Impact of Encumbrance on Mobile Interactions

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Abstract. This paper investigates the effects of encumbrance (holding different types of objects while using mobile devices) to understand the interaction difficulties that it causes. An experiment was conducted where participants performed a target acquisition task on a touchscreen mobile phone while carrying different types of bags and boxes. Mobility was also evaluated since people carry items from one place to another. Motion capture hardware was used to track hand and arm postures to examine how holding the different types of objects caused excessive movement and instability therefore resulting in performance to decline. The results showed encumbrance and mobility caused target accuracy to decrease although input while holding the box under the non-dominant arm was more accurate and exerted quicker targeting times than holding no objects. Encumbrance affected the dominant hand more than the non-dominant hand as targeting error significantly increased and caused greater hand instability. The issues caused by encumbrance suggest the topic requires more attention from researchers and users would benefit greatly if better interaction techniques and applications are developed to counteract the problems.

Keywords: Encumbrance, Mobility, Mobile interactions, Target acquisition.

1 Introduction

Mobile devices such as smartphones play a vital role in our everyday activities as they allow users to perform common tasks such as talking to friends, emailing documents to colleagues and searching for nearby services while on the move.

As a result, mobile devices are being used in a wide range of different contexts and it is important to examine if users experience interaction and usability difficulties when faced with potentially demanding multitasking situations. One context that has not been explored in great depth is studying users when they are encumbered: holding typical objects as such handbags, umbrellas, shopping bags and boxes while engaging with their devices simultaneously. People frequently carry these objects while walking from one place to another and as a result, users often need to use their phones at the same time to send messages, look at maps or refer to other services. Therefore, encumbrance and mobility is closely linked with each other. Using a mobile phone in these kinds of situations while physically hampered is challenging as it can be awkward to see the screen and make input. It would be valuable to understand how encumbrance affects interactions with touchscreen mobile devices so that better input techniques and error detection could be developed to negate the issues and problems it causes. Also, carrying different types of objects may have a different impact on the user thus it is beneficial to be able to categorize the different types of encumbrances by the way they affect the user's performance when interacting with mobile devices.

Since users are likely to carry objects between places, it is also imperative to examine how walking and encumbrance together affect input performance on touchscreen mobile devices. The physical motion required to walk naturally causes the user's arm to move and swing in phase with each foot step. However, this natural stance is disrupted when attention from the mobile device is required as the user attempts at steadying their constantly moving arm and hand to input. The effects of encumbrance is likely to cause interaction to become even more physically demanding and put significant pressure on the user's mental ability to multitask as they walk and navigate the surrounding area while avoiding nearby obstacles. The issues caused by walking alone on mobile interactions have previously been investigated in great detail as researchers have developed various solutions to assist the user to input more accurately [3] and [4]. However, it is unclear what further issues the introduction of encumbrance causes on interaction when the user is walking. Therefore, it is important to understand if performance is further worsened by encumbrance and to detect new usability problems that previously have been overlooked. It would also be interesting to see if encumbrance and mobility causes distinctive interaction issues therefore better applications could be developed to assist the user to maintain a good control of their devices in realistic multitasking situations.

To examine the effects of encumbrance and mobility on mobile interactions, we defined a set of common objects that users frequently carry to be assessed in our experiment. There is a large number of possible objects that people hold in their daily activities and the issue is further complicated the object's characteristics such as its size, shape, heaviness and quantity. Also, a particular object could be held in various different ways which normally depend on personal preference and the context the person is currently in. As a result, it is important to focus on the typical strategies that users perform while encumbered in order to simultaneously use their mobile device. An observational study was carried out to find the most common types of objects and the way they were being carried in a range of public settings. Based on the results collected from the study, the encumbrance experiment examined two types of objects: holding a bag in hand and carrying a box underarm. A target acquisition task was used on a touchscreen mobile phone to evaluate the effects of the two types of encumbrances and mobility. The participants performed target selections on a touchscreen mobile phone and holding the different types of objects at the same time while either standing still or walking to simulate realistic encumbrance scenarios. To investigate how holding the different types of bags and boxes cause targeting difficulties, motion capture cameras were used to track hand and arm movements during interaction. The assumption was that carrying different objects while walking will cause more physical movements and instability to the user's hand and arm which makes it more challenging for the user to maintain a steady position to input accurately on the touchscreen device.

2 Background

This section of the paper will review the related literature with the first part discussing research that has examined encumbrance and the second part reviewing studies on mobile interactions while walking.

2.1 The Effects of Encumbrance

There has been little research that specifically examined the interaction problems caused by encumbrance due to holding common objects.

Ng *et al.* [10] studied the topic of encumbrance by examining wrist rotation gestures as a novel hands-free and eyes-free interaction technique to reduce the issues caused by holding a bag and box when interacting with a mobile phone. A small bag and a rectangular box were evaluated to replicate some of the effects of carrying cumbersome objects. The main motivation behind the study was to illustrate that holding common objects does have an impact on mobile interactions and different types of objects have a different impact on the user's performance. The findings from their Fitts' Law targeting experiment suggested holding the bag caused users to become less accurate while the performance of carrying the box underarm was similar to unencumbered. The swinging motion caused when holding the bag made it difficult to steady the arm for input while the users were able to stabilize their forearm when gripping the box in place which helped them to perform wrist gestures more easily. Target movement times between the two types of encumbrances were not significant. The study also showed that sensor components such as gyroscopes that are found in most modern mobile devices could be used to detect precise wrist orientation and movements and therefore support the user when they are physically hindered.

Oulasvirta and Bergstrom-Lehtovirta [13] studied the relationship between holding a group of smaller-sized objects and input accuracy on different computing devices. Twelve different multitasking situations were examined which covered a range of hand grips and arm postures while holding a variety of everyday items such as a writing pen and a beverage cup. Participant performed the various types of encumbrances while selecting targets on a laptop computer via mouse and trackpad input and text entry by different forms of keyboards on a mobile phone. The results showed that holding objects such as a pen while performing the target selection task on the laptop by mouse input caused performance to decline more than the trackpad. One-handed text entry on the mobile device while holding an object (such as a pair of scissors) caused a decrease in performance when compared to two-handed input especially with single-handed stylus targeting since it normally requires both hands to input. Interestingly, text entry via a virtual keyboard exerted better results than the physical equivalent as more finger pressing pressure is required. The study examined a set of interesting manual tasks and included activities that require a pushing action rather than the common holding grip in hand. One final point that the study makes is the notion of safety as there are situations where it may not be possible to prevent hindrance when using mobile devices (for example, holding small children). Better context detection systems and more effective input techniques are required to help users during interaction when confronted with these challenging situations. Wolf [17] assessed how people performed manual tasks by examining hand grips and positions in order to explore the areas that are free to perform secondary interaction activities.

Mainwaring *et al.* [8] conducted an ethnographic study across three major cities to examine the personal connection between the items that people carried and how these items were used in their daily context with surrounding people and interfaces. Items were classified into various categories such as those which distracted the user from the environment (music players, phones and books), personal belongings (wallets, keys, make-up) and professional tools (laptop, PDAs). The findings from the study suggested different items have its own unique personal value and as a result different objects may have a varied impact on interaction with mobile devices. The issue of a particular object's personal value to the user creates an unusual viewpoint on encumbrance. For example, dropping a wallet could be more disastrous and frustrating to the user than a mobile phone while on the move. It would be worthwhile to investigate if this is the case and if objects can also be grouped by personal value rather than the standard categories of the object's size, shape or how it obstructs the user.

Tamminen *et al.* [16] observed how outdoor environments constantly compete for the user's attention and discovered repeated instances where the user's hands were busy performing activities ranging from holding a newspaper while travelling between locations to clutching a cigarette packet while searching for money placed in the person's pockets. Performing several activities at the same time is likely to cause the user difficulty in dividing its visual attention to complete each individual task successfully as discussed by [12]. There needs to be more efficient interaction methods and alternative techniques to assist the user when they are physically impaired and visually distracted. People carry personal belongings and objects from one place to another therefore it is also important to examine the impact mobility has on mobile interactions and its relationship with encumbrance.

2.2 The Effects of Mobility

The interaction difficulties caused by walking while using mobile devices have been well documented.

Bergstrom-Lehtovirta *et al.* [2] examined the relationship between target selections on a touchscreen mobile phone and the user's preferred walking speed (PWS) on a treadmill. The results showed that when users walked approximately between 40 - 80% of their PWS, performance began to level as users were able to stabilize the dominant hand more successfully to input more accurately on the touchscreen mobile phone. Mizobuchi *et al.* [9] recorded an average walking speed of 1.77 km/h when examining the relationship between mobility and button size. This finding is much lower than the walking speed of an average adult human being [5]. It is important to see if holding different types of objects cause the user to reduce their walking speed even further and if the slowdown in pace meant that users were able to keep a reasonable level of input accuracy and performance.

Kane *et al.* [4] attempted to compensate some of the problems caused by mobility by developing Walking User Interfaces (WUI) which dynamically change the characteristics of interface widgets to support the user to input more effectively while walking. The results showed a trade-off between button size and the amount of effort and time required to scroll the screen to make the appropriate selection. This was also discussed by Schildbach and Rukzio [15]. The performance of their WUI prototype was comparable to an equivalent static interface although it was not as effective as a fixed layout with larger sized buttons. Goel *et al.*[3] and Nicolau and Jorge[11] have also studied the issues of walking and developed better text entry systems to help typing on touchscreen mobile devices. It would be useful to examine if these applications and similar interfaces are still as effective and could solve some of the interaction problems caused by encumbrance.

Brewster [1] showed that button pressing on a PDA was more accurate and subjectively easier when the user was sitting down compared to walking outdoors. A drop in performance of approximately 30% was recorded and one possible cause could have been due to the increased mental attention required to walk and navigate the environment while engaging with the mobile device at the same time. The effects of encumbrance may result in error rate to increase further between standing and walking. The other aspect that is worth considering is evaluating walking-based experiments in laboratory settings and outdoor environments. Our experiment was conducted inside a quiet room due to the restrictions of the motion capture hardware. Consequently, this may have had an undesired effect on targeting performance when carrying the different types of objects since the indoor environment is much calmer than a real world setting therefore making the context less challenging for the user. However, Lin *et al.* [7] suggested using an artificial route with obstacles to increase the user's cognitive workload to a level similar to walking in outdoor settings.

Moving away from HCI literature to examine how walking affects the user's mental performance, Lajoie *et al.* [6] discussed attentional demands for static and dynamic tasks. The dual-task procedure was used where subjects reacted to auditory stimuli in three different mobility positions (sitting, standing and walking). The results showed walking required more cognitive attention than standing and sitting down due to the additional motion of balance needed to walk. Pellecchia [14] examined the relationship between mental demands and muscle motor movements and indicated that by increasing the difficulty of the cognitive task resulted in greater body movements in terms of postural sway. This suggests there is a close relation between the person's cognitive abilities and human motor performance. If walking alone can cause increased mental stresses on the user, it is important to examine if encumbrance creates similar cognitive difficulties therefore affecting the user's ability to engage with mobile devices effectively when interaction is required.

The limited research on encumbrance suggests the topic is at its early stages and a better understanding into the usability problems it causes can be beneficial to mobile device users. Although many studies have examined the issues of walking during interaction and solutions have been developed to enhance the user experience, the effects of mobility combined with encumbrance may result in much greater problems therefore it is crucial to examine if such issues do occur. The next section of the paper will discuss the methodology of our experiment which was conducted to investigate the impact of carrying different types of objects on targeting performance on a touchscreen mobile phone.

3 Methodology

The section will be split into three parts to describe the procedure taken for the encumbrance experiment.

The first part will discuss the initial observational study conducted to classify the most common objects that users were seen to carry and to choose two types of those objects to be evaluated in the experiment. The second part will describe the use of a motion capture system to detect hand postures and body movements and how users interacted with the mobile phone when encumbered and walking. The third part will describe the target acquisition task and the design of the experiment.

3.1 Common Types of Encumbrance Objects

The main purpose of the observational study was to examine the objects that users were seen to carry regularly while using a mobile device and to group those objects into suitable categories.

Since there is a vast amount of possible objects that could encumber the user, it is essential to identify and concentrate on the most common types of objects that are likely to be held during interaction. In order to define a set of encumbrance objects to be assessed in the experiment, three different types of public locations were observed (main street, transport station and supermarket) to examine the wide variety of objects that people held and carried. The experimenter would observe the general public during peak times for two hours at each type of location (for example, early commuting hours between 8am to 10am at a railway station and lunch period between 12pm and 2pm in a supermarket) since there will be a great influx of people and the probability of seeing a range of different objects is increased. Two different sites for each type of location were observed which resulted in six set of data. Each object seen being held or carried was noted down in terms of the following characteristics: *type, shape (rectangular or round?), size (length, width & thickness), quantity, input hand (non-dominant, dominant or both), hand action and grip required, and arm posture*.

Once the observational study was completed, the data collected was firstly grouped by object type and then sorted by how often it was noted down during the study. The results showed that different types of bags were the most frequently held objects as it account for 49% of all the items recorded. Boxes were the second most common object with 35% while the remaining 16% of objects documented ranged from beverage cups, umbrellas, specialized equipment to children, prams and pet leashes. The objects recorded were also separately categorized based on the arm movement and hand actions required by the user. There were four main categories: 1. *swinging* –

objects such as bags and holding a child's hand were placed into this group as it caused the arm to swing somewhat unpredictably; 2. *bulky* - boxes were grouped into this class as people were seen to hold different types of boxes normally underarm which required an awkward but assuring grip from the arm to prevent the object from falling to the ground; 3. *push and pull* - objects such as prams and trolleys were put into the *push* class while people were seen *pulling* wheeled luggage; and 4. *complex* – objects in this category included keys, wallets and hot beverages which require more careful and intricate finger action and grip.

Based on our observations of people in the public environment, different types of bags and boxes were chosen as the encumbrance objects to be evaluated in the experiment. Since there was a great variety of bags and boxes noted during the observation, the decision was made to evaluate two different types of each object based on its size and shape. Therefore, the experiment assessed two bags (small and medium sized) and two boxes (thin and thick broadness). The small bag represented a handbag while the medium bag simulated people carrying a shopping bag. The dimensions (width x height x depth) of the small and medium bags were 35 x 25 x 17 cm and 45 x 55 x 25 cm respectively. The thin and thick boxes measured 37 x 30 x 15 cm and 39 x 30 x 29 cm respectively. The bags were held in hand while the boxes were carried underarm as people were seen to adopt these strategies during the observational study. All bags and boxes weighed 3kg each to keep the object's heaviness consistent. The weight of 3kg was chosen to simulate the effects of carrying realistic objects that would make interaction physically difficult yet limit the amount of physical straining on the participants. The objects and the method that they were held during the experiment are shown in Figure 1.

Fig. 1. The four objects evaluated in the experiment. From left to right: small bag, medium bag, thin box and broader box. The images show how each object was held in the non-dominant hand or arm.

3.2 Tracking Hand and Arm Motions

To understand how holding the different objects encumbered the user and to analyze the level of hand and arm instability, a Vicon motion capture camera system was used (http://www.vicon.com). Twelve infrared cameras sampling at 120Hz recorded body movements (to a thousandth of a millimetre) in three-dimensions by tracking reflective markers which were firmly attached to each participant at specific body locations to track their movements while performing the experimental task in the capturing volume. The reflective markers were placed on the front and back of the upper torso and the hand and arm areas. A total of 15 markers were attached to each participant and Figure 2 illustrates their location.

The marker on the neck was used to calculate the total distance walked and the average walking speed for each participant. The right and left shoulder and left thumb markers (all participants were right handed therefore the mobile device was held in the left, non-dominant hand) were used to determine the relative position between the device and the user to calculate the amount of hand movement along each dimension. One marker was attached to the right index finger (intermediate phalanx section) to track the motion of the input finger. It would have been more appropriate to place the marker on the tip of the index finger but due to the size of the markers it would have obscured part of the touchscreen and made targeting more difficult. The remaining markers were used to define sections of the body. Participants were asked to avoid wearing loose clothing and long hair was tied up in a head cap provided to avoid excessive marker movement and prevent the markers from being occluded.

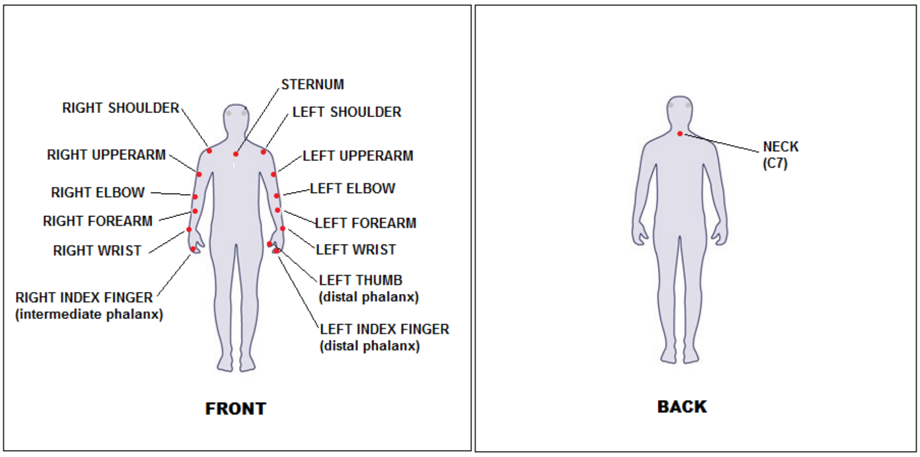

Fig. 2. The location of the reflective markers (red dots) placed on each participant.

3.3 Experimental Task

The experimental task was to select a series of crosshair targets one at a time on a touchscreen mobile phone. The participants had to select the current target crosshair (colored green) as quickly and as accurately as possible. The screen also showed the location of the next target (colored red) so that the participants always knew where to input next until they reached the last target. There were one hundred targets aligned in a 10 x 10 grid across the screen which were randomly ordered for each condition. Each target border measured (width x height) 40 by 60 pixels with the central cross-hair measuring 10 pixels in each direction (1 pixel = 0.1mm). A gap was created between the last row of the targets and bottom of the touchscreen to prevent the participants accidentally tapping the soft keys. The task ran on a Google Nexus One Android 3.1 smartphone as shown in Figure 3.

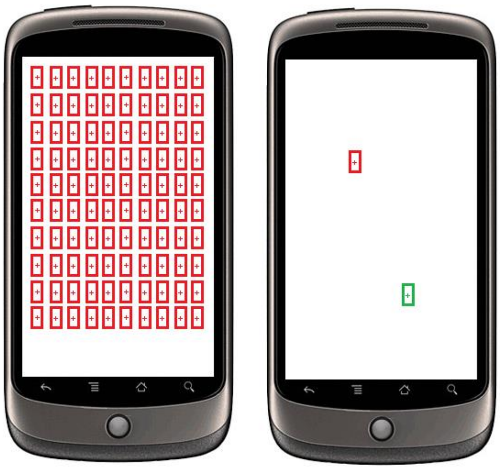

Fig. 3. The image on the left side illustrates the layout of the targets while the experimental task is shown in the right side image.

3.4 Experimental Design

A within-subjects design was used for the experiment and each participant completed the target acquisition task while unencumbered (holding nothing) and carrying each of the four objects in either the dominant or non-dominant side.

As a result, there were nine encumbrance levels and each level was evaluated either standing still or walking which gave 18 conditions in total. The participants stood at the centre of the capturing volume for the standing conditions and navigated a pre-defined rectangular route (the outer and inner borders were 2.8 x 3 meters and 1 x 1.4 meters respectively) for the walking conditions as shown in Figure 4. The dimensions of the route were limited to the position of the cameras. Participants were instructed to keep within the path and walked in a clockwise direction. Each participant's preferred walking speed (PWS) was calculated before the experiment began. The participants were asked to navigate the route for two minutes at a pace that they normally would if they were walking on a quiet street.

The conditions were randomly ordered for each participant to reduce learning effects. 18 participants (4 males, 14 females) aged between 19 - 38 years and all right handed were recruited from the university to take part in the experiment. The Independent Variables were encumbrance and mobility. The Dependent Variables were targeting accuracy, targeting speed and the level of movement in the non-dominant hand holding the device. The hypotheses were:

H1. Targeting accuracy significantly decreases when the user is encumbered and walking compared to unencumbered and standing still.

H2. Targeting speed is significantly slower when the user is encumbered and walking compared to unencumbered and standing still

H3. Targeting is less accurate when the dominant hand or arm is encumbered compared to the non-dominant hand or arm carrying the objects.

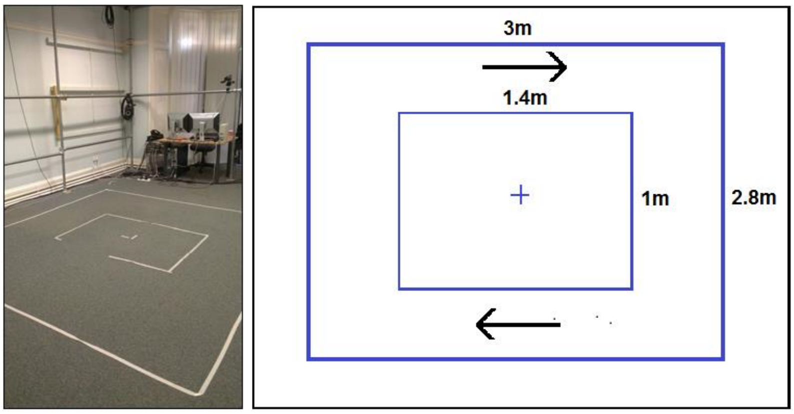

Fig. 4. The left image shows the actual capturing area. The right image illustrates the dimensions of the pre-defined path. Participants stood at the centre for the standing conditions.

4 Results

To eliminate unintentional target selections, the recorded target positions that were greater than 70 pixels horizontally and 110 pixels vertically from the centre of the target crosshair were removed from the final data analysis.

The reason for choosing the specific limit was to permit one target size margin of error. Target accuracy was measured as the distance (in pixels) from the centre of the target crosshair to the position recorded on the touchscreen. Speed of input (in seconds) was the time taken to select the current target.

4.1 Target Accuracy and Target Speed

A two-factor repeated-measures ANOVA with type of encumbrance and mobility as factors was calculated to examine both target accuracy and target speed.

The x-axis and y-axis were analysed independently for accuracy to assess if there was more error in a particular direction. For target accuracy on the x-axis, there was a significant main effect for stance, F(1,17) = 69.358, $p < 0.05$ and for encumbrance, F(8,136) = 7.131, $p < 0.05$. The interaction was also significant F(8,136) = 2.658, $p < 0.05$. A pairwise comparison for encumbrance with Bonferroni corrections showed that unencumbered was more accurate than holding the bags in either hands and carrying the thin and thick boxes under the dominant arm. However, carrying either the thin or thick box under the non-dominant arm was not significantly less accurate than holding no objects. Also, carrying the thin box under the non-dominant arm was more accurate than holding the wider box under the dominant arm. Table 1 illustrates the pairwise comparisons that were significant for encumbrance on targeting accuracy along the x-axis.

Table 1. The table shows the pairwise comparisons for encumbrance that were significantly different for accuracy on the x-axis. *Adjustment for multiple comparisons: Bonferroni.

Comparison		Mean Diff.	Std. Err.	Sig.*
Unencumbered	Small bag (non)	-2.718	0.690	0.038
Unencumbered	Small bag (dom)	-3.490	0.874	0.034
Unencumbered	Medium bag (non)	-3.366	0.461	0.000
Unencumbered	Medium bag (dom)	-5.248	0.973	0.002
Unencumbered	Thin box (dom)	-4.463	1.048	0.019
Unencumbered	Thick box (dom)	-4.952	0.928	0.002
Thin box (non)	Thick box (dom)	-4.063	0.966	0.021

Similarly for input accuracy along y-axis of the screen, there was a significant main effect for mobility, F(1,17) = 25.901, $p < 0.05$ and for encumbrance, F(8,136) = 4.022, $p < 0.05$. The interaction between the two factors was also significant F(8,136) = 2.334, $p < 0.05$. The participants were more accurate while standing than walking. A pairwise comparison with Bonferroni adjustment showed that unencumbered was only significantly more accurate in the vertical direction than holding the medium bag in the dominant hand (mean difference = -3.927, std. error = 0.933 and p =0.021). All other encumbrance comparisons were not significantly different ($p > 0.05$). Figures 5a and 5b illustrate the mean target accuracy for the x-axis and y-axis of the touchscreen respectively. Based on the results for accuracy, hypothesis H1 is rejected since holding the boxes in the non-dominant hand was not significantly less accurate than unencumbered. Also, carrying the medium bag in the dominant hand was the only hindrance that caused accuracy to be significantly worse than holding no objects in the y-axis. Standing was significantly more accurate than walking.

The results for targeting speed from conducting an ANOVA indicated a significant main effect for encumbrance; F(8,136) = 13.239, $p < 0.05$ and mobility; F(1,17) = 12.230, $p < 0.05$. The interaction was also significant F(8,136) = 3.257, $p < 0.05$. Unexpectedly, holding the medium bag and both boxes in the non-dominant side caused selection times to be significantly lower than unencumbered. Hypothesis H2 is rejected based on this finding. Also, targets took significantly less time to select when carrying each of the four objects in the non-dominant hand or arm than the dominant side. Figure 6 illustrates the mean targeting times for each condition.

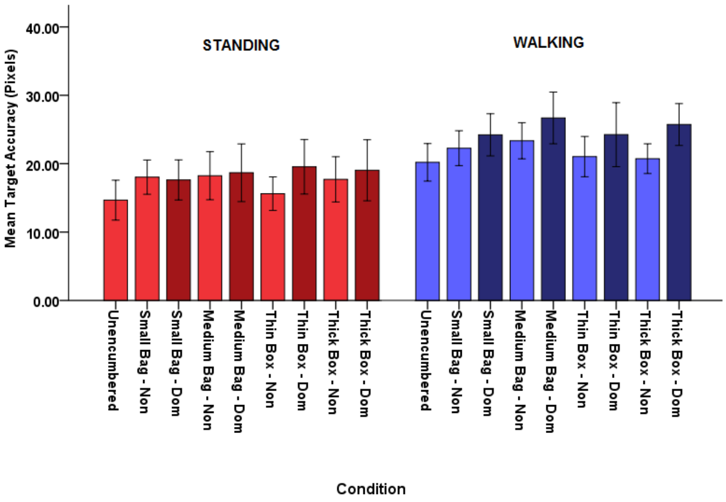

Fig. 5a. Mean target accuracy along the x-axis of the touchscreen (95% CI). The red and blue bars represent the standing and walking conditions respectively. The lighter and darker shade of each color indicates holding the objects in the non-dominant and dominant sides respectively.

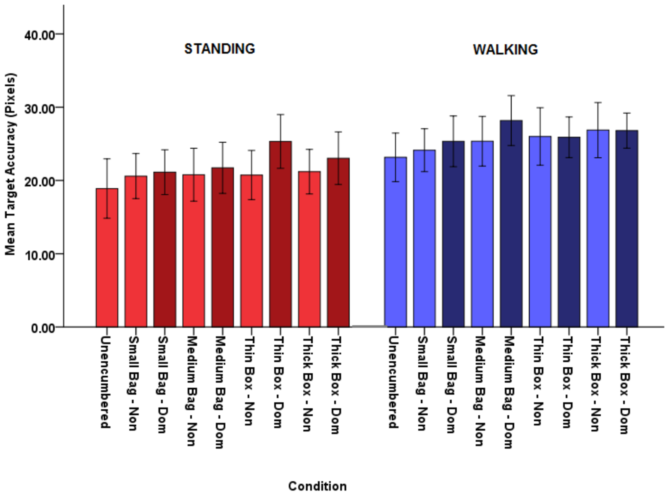

Fig. 5b. Mean target accuracy along the y-axis of the touchscreen (95% CI). The color representation for the conditions is the same as Fig. 5a.

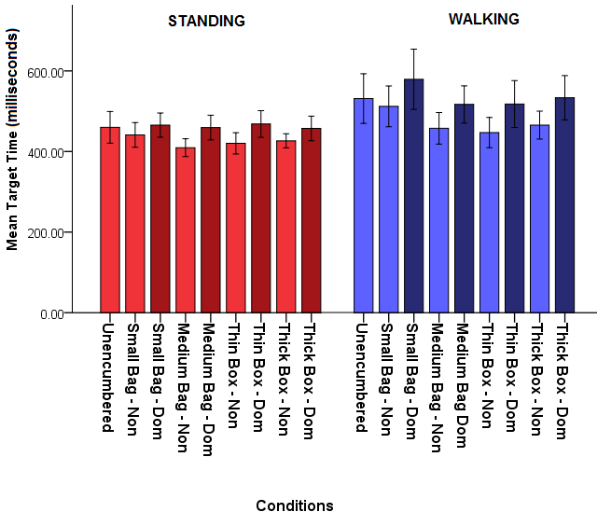

Fig. 6. The mean targeting speed (seconds) for each condition (95% CI). The color representation for the conditions is the same as Fig. 5a.

4.2 Preferred Walking Speed (PWS)

Table 2 shows the drop in the participants' preferred walking speed (PWS) for each type of encumbrance while performing the task compared to walking alone and no interaction.

Holding the broader box under the non-dominant arm caused the highest decline in PWS of approximately 41%. Each encumbered condition's drop in PWS was greater than the results reported by [2], who found a 24% decline in PWS when performing a similar pointing task to ours on a treadmill. This suggests that carrying different types of objects during interaction may further affect the user's walking pace.

Table 2. The decrease in PWS (%) while holding the different types of bags and boxes compared to no interaction.

Condition	Drop in PWS (%)	
Unencumbered	16.68	SD = 9.46
Small bag (non-dominant)	25.17	SD = 11.96
Small bag (dominant)	27.64	SD = 12.09
Medium bag (non-dominant)	30.48	SD = 13.17
Medium bag (dominant)	31.49	SD = 13.17
Thin box (non-dominant)	36.88	SD = 13.45
Thin box (dominant)	33.48	SD = 14.76
Thick box (non-dominant)	41.06	SD = 11.64
Thick box (dominant)	36.48	SD = 11.67

4.3 Analysing Hand Movements

The motion capture data was processed to examine the movements of the non-dominant hand which held the mobile phone to see if carrying the different types of objects chosen for our experiment caused the user difficulty to steady their hands for input.

The markers placed on the non-dominant hand (left thumb and left index finger) and both shoulders were used to calculate the relative position between the device and the participant to determine the change in movement on each axis. The x-axis, y-axis and z-axis of motion represents left – right, forward – backward and upwards – downwards movements respectively. These notations will be used when discussing hand movements to avoid confusion with describing target accuracy.

Encumbrance was grouped by the hand or arm carrying the object (i.e. dominant vs. non-dominant) rather than the actual object itself when analyzing hand movements. This was a more appropriate method to understand how holding different objects impacts handedness and to identify where the problem is occurring. A two-way ANOVA with mobility and handedness (non-dominant vs. dominant) as factors was calculated to examine its effect on input accuracy. The results showed there was a significant main effect for mobility; $F(1,71) = 133.369$, $p < 0.05$ and for handedness; $F(1,71) = 19.309$, $p < 0.05$. The interaction was also significant $F(1,71) = 12.753$, $p < 0.05$. Pairwise comparisons with Bonferroni adjustment showed the participants were less accurate when the dominant hand was encumbered compared to the non-dominant hand. The mean target accuracies for the dominant and non-dominant sides while standing and walking are shown in Table 3.

Table 3. The mean target accuracy (pixels) when the non-dominant and dominant hand/arm was encumbered.

	Target Accuracy (pixels)	
Non-dominant. – Standing	17.402	SD = 5.965
Dominant – Standing	18.723	SD = 7.784
Non-dominant. – Walking	21.846	SD = 5.201
Dominant – Walking	25.221	SD = 7.370

The amount of movement of the non-dominant hand holding the mobile phone was assessed in each direction separately to see if encumbrance caused more movement and instability on a particular axis. The mean hand movement (mm) was calculated by processing the amount of motion between three tenths of a second prior to a target being selected and the instance the tap onscreen was recorded.

A two-factor repeated-measures ANOVA with mobility and handedness as factors was conducted in each direction to assess if there was a significant difference in mean movement on the hand or arm carrying the bag and the box. For left and right direction of movement, there was a significant main effect for mobility; $F(1,27) = 791.591$, $p < 0.05$ and encumbered hand; $F(1,27) = 240.090$, $p < 0.05$. The interaction was significant $F(1,27) = 51.422$, $p < 0.05$. For forward and backward movement, ANOVA showed a significant main effect for mobility; $F(1,27) = 855.252$, $p < 0.05$

and encumbered hand; F(1,27) = 188.013, $p < 0.05$. The interaction was significant F(1,27) = 24.424, $p < 0.05$. The results for upward and downward movement indicated a significant main effect for stance; F(1,27) = 1255.995, $p < 0.05$ and encumbered hand; F(1,27) = 61.908, $p < 0.05$. The interaction was significant F(1,27) = 459.970, $p < 0.05$. Table 4 shows the mean movement in each direction of the non-dominant hand while encumbered and either standing still and walking the route.

Table 4. The mean movement of the left hand holding the mobile phone in each direction while encumbered. (S) and (W) represent standing and walking respectively.

Encumbered Hand/Arm	Movement Direction	Mean Movement (mm)	Std. Dev.
Non-Dominant (S)	Left/Right	1.411	0.262
Dominant (S)	Left/Right	4.781	1.11
Non-Dominant (W)	Left/Right	5.338	0.922
Dominant (W)	Left/Right	6.648	0.611
Non-Dominant (S)	Forward / Backward	0.697	0.232
Dominant (S)	Forward / Backward	2.505	0.414
Non-Dominant (W)	Forward / Backward	4.044	0.667
Dominant (W)	Forward / Backward	4.862	0.760
Non-Dominant (S)	Upward/Downward	0.991	0.273
Dominant (S)	Upward/Downward	3.286	0.499
Non-Dominant (W)	Upward/Downward	5.939	0.550
Dominant (W)	Upward/Downward	6.365	0.664

When the participants were standing still, carrying the objects in the dominant hand caused the other hand (holding the device) to move significantly more in each of the three directions when compared to the non-dominant hand being encumbered. The difference in mean hand movement between the non-dominant and dominant side being encumbered was very similar while walking. However, walking caused a significant increase of movement in both the non-dominant and dominant sides when compared to standing still. The results support hypothesis H3 as holding the bags and boxes in the dominant side resulted in significantly more movement in the hand holding the device and caused input to become less accurate when compared to the non-dominant side being hindered.

5 Discussion

The results from the experiment have shown that holding different types of bags in hand or carrying boxes underarm caused a negative impact on targeting performance on a touchscreen mobile phone.

The participant’s input performance has illustrated that holding the objects chosen for our experiment caused targeting to become less accurate particularly when the object is being held in the dominant hand which was also targeting at the touchscreen to input at the same time. Interestingly, there was no significant effect for accuracy between unencumbered and carrying the two differently sized boxes under the non-dominant arm. Furthermore, performing the experimental task while unencumbered took significantly longer to input than holding the medium bag and both types of boxes. [10] reported the performance of wrist gestures while carrying a box under the dominant arm was similar to unencumbered since users were actually able to use the box to assist their input. In terms of assessing the effects of mobility, walking while encumbered in general caused input to become less accurate and required more time to select the targets onscreen. The non-dominant hand which held the mobile phone was tracked to examine the level of movement caused by carrying the different types of objects. There was significantly more movement and instability when the dominant hand or arm was hampered compared to the non-dominant side. The difference in the amount of movement between encumbering the dominant and non-dominant sides was very similar when walking compared to standing still which may suggest walking alone could have an overwhelming effect on interaction.

Observing how the participants held the bags and boxes provided a valuable insight of some of the physical difficulties that users may experience when interacting with mobile devices while encumbered. The expectation was that carrying the thinner box underarm would be physically less challenging than the wider box. However, watching the participants suggested that the thinner box caused more problems to hold in place to avoid it being dropped to the ground especially when walking the route. Comments from the participants revealed the thinner box kept slipping down from their arms and it was difficult to find a comfortable gripping position while performing target selections, especially when carrying the box under the dominant arm. Surprisingly, the broader box did not cause as much physical issues as the thin box once a secure carrying posture was found. But, a few participants did find it uncomfortable to carry the wider box over a long period of time due to the length of their arms which may have caused selecting the targets more difficult and performance to decline.

The majority of participants had little trouble holding the two types of bags during interaction as the physical issues were more due to fatigue and tiredness. A number of participants commented that it was physically unpleasant to carry the bags due to the handles causing discomfort to their hands which may have caused targeting performance to decline. Holding the medium bag required a more restrictive upright arm position to prevent the bag from touching the floor. The participants mentioned that it was more demanding to hold both type of bags in the dominant hand and input at the same time compared to carrying the objects in the non-dominant hand. Furthermore, when standing still, it was evident that the dominant hand started to move downwards as the arm began to tire which would have made viewing the touchscreen more awkward and caused input to become more challenging. Remarks from the participants suggested that holding both types of bags in the dominant hand while walking the route required considerably more effort to control and maintain the forearm in a steady posture to target at the screen as the bag unpredictably swings from side to side. Also, it was fascinating to examine the different strategies adopted by the participants to carrying the different types of bags and boxes. Although we instructed the participants to carry the boxes underarm and the bags in hand, each participant's method of carrying the objects was slightly different and unique to the individual. This was more apparent when holding the box underarm as the participants with shorter arm lengths found it more challenging to grip the box and had to adjust their arm position at regular intervals to make input easier.

A simple recommendation that may improve input performance of two handed interaction while encumbered is to avoid carrying objects in the dominant hand or arm. However, in realistic situations, it may not be possible to switch holding the objects to the non-dominant hand only as the user could be occupied by carrying multiple objects. We need to design and develop effective techniques and applications to help users input more accurately when encumbering the dominant hand is unavoidable. One possibility is to increase target size to give the user a bigger margin of error. However, this would require careful interface design as it limits onscreen space for other widgets as discussed by [4]. We also propose that future studies should revisit previous research which have developed enhanced methods to assist users to input more efficiently while on the move. For example, Goel *et al.* [3]'s WalkType application has shown to improve text entry while the user is walking. A repeated study that examined both encumbrance and mobility would indicate if the application is still as effective and could be used to reduce some of the issues caused by encumbrance. A final suggestion on future studies is to assess the impact of carrying a wider range of objects and include different hand gripping positions such as those that require a pushing action to extend our knowledge into the effects of encumbrance on mobile interactions.

6 Conclusions

The main purpose of the study was to examine the impact of encumbrance and make researchers aware of the usability issues and difficulties when users are physically hampered during interaction with mobile devices.

An observational study was conducted to investigate the typical objects that people frequently held and carried in their everyday activities. Based on the results, we evaluated different types of bags and boxes to simulate realistic cumbersome and physically challenging situations that users are likely to encounter. The results from our main experiment showed that encumbrance caused targeting accuracy on a touchscreen phone to decline compared to holding no objects. However, targeting while carrying the thinner box under the non-dominant arm was significantly quicker and more accurate than unencumbered or holding the box in the dominant side. Moreover, targeting was less accurate when the dominant hand or arm was physically hampered during interaction and tracking the motion of left hand (which held the mobile phone) showed there was significantly more movement compared to the non-dominant side was carrying the objects. This suggests that we should focus on assisting the user to input more accurately especially when the dominant hand and arm is encumbered.

Encumbrance also affected the user's preferred walking speed and although input was significantly less precise when the user was walking compared to standing, the performance difference was not as great as expected. Further investigation is required to see if there is a tradeoff between walking speed and encumbrance and assess input performance when the user has to maintain their PWS while encumbered. We hope the study presented in this paper has motivated researchers to develop better interaction techniques to aid users to input more effectively on touchscreen mobile devices.

References

1. Brewster, S. A. Overcoming the lack of screen space on mobile computer. Personal and Ubiquitous Computing 6 (2002), 188-205.
2. Bergstrom-Lehtovirta, J., Oulasvirta, A., and Brewster, S. The Effects of Walking Speed on Target Acquisition on a Touchscreen Interface. *In Proc. MobileHCI2011*, ACM Press (2011), 143-146.
3. Goel, M., FindLater, L., and Wobbrock, J. WalkType: using accelerometer data to accommodate situational impairments in mobile touchscreen text entry. In *Proc. CHI2012*, ACM Press (2012), 2687-2696.
4. Kane, S. K., Wobbrock, J. O., and Smith, I. E. Getting off the treadmill: evaluating walking user interfaces for mobile devices in public spaces. *In Proc. MobileHCI2008*, ACM Press (2008), 109-118.
5. Knoblauch, R., Pietrucha, M., and Nitzburg, M. Transportation research Record, 1996, 1538(-1), 27-38.
6. Lajoie, Y., Teasdale, N. Bard, C. and Fleury, M. Attentional demands for static and dynamic equilibrium/ In *Experimental Brain Research*, 97, 1(1993), 139 – 144.
7. Lin, M., Goldman, R., Price, K. J., Sears, A., and Jacko, J. How do people tap when walking? An empirical investigation of nomadic data entry. Intl. J. of Human Computer Studies, 65, 9 (2007), 759-769.
8. Mainwaring, S., Anderson, K., and Chang, M. Living for the global city: mobile kits, urban interfaces, and ubicomp. In *Proc. UbiComp2005*, Springer-Verlag (2005), 269-286.
9. Mizobuchi, S., Chignell, M., and Newton, D. Mobile text entry: relationship between walking speed and text input task difficulty. In *Proc. MobileHCI2005*, ACM Press (2005), 122-128.
10. Ng, A., Brewster, S. and Crossan, A. The Effects of Encumbrance on Mobile Gesture Interactions. In Proc. of Body, Movement, Gestures & Tactility in Interaction with Mobile Devices, workshop at MobileHCI 2011, (Stockholm, Sweden).
11. Nicolau, H., and Jorge, J. Touch typing using thumbs: und understanding the effect of mobility and hand posture. In *Proc. CHI2012*, ACM Press (2012), 2683-2686.
12. Oulasvirta, A., Tamminen, S., Roto, V., and Kuorelahti, J. Interaction in 4-second bursts: the fragmented nature of attentional resources in mobile HCI. *In Proc. CHI2005*, ACM Press (2005), 919-928.
13. Oulasvirta, A., and Bergstrom-Lehtovirta, J. Ease of juggling: studying the effects of manual multitasking. In *Proc. CHI2011*, ACM Press (2011), 3103-3112.
14. Pellecchia, G. Postural sway increases with attentional demands of concurrent cognitive task. In Gait Posture, 18, 1 (2003), 29-34.
15. Schildbach, B. and Rukzio, E. Investigating selection and reading performance on a mobile phone while walking. In *Proc. MobileHCI2010*, ACM Press (2010), 93-102.
16. Tamminen, S., Oulasvirta, A., Toiskallio, K., and Kankainen, A. Understanding mobile contexts. In Personal Ubiquitous Computing, 8 (2004),135-143.
17. Wolf, K. Microinteractions beside ongoing manual tasks. In Proc. TEI11, ACM Press (2011), 447-448.